Solar Power

Solar thermal – Incoming solar radiation is use to heat water (or some other working fluid) to high temperature. The fluid is then flashed to steam driving a turbine and generating electricity.

Photovoltaic – direct conversion of solar radiation to electricity.

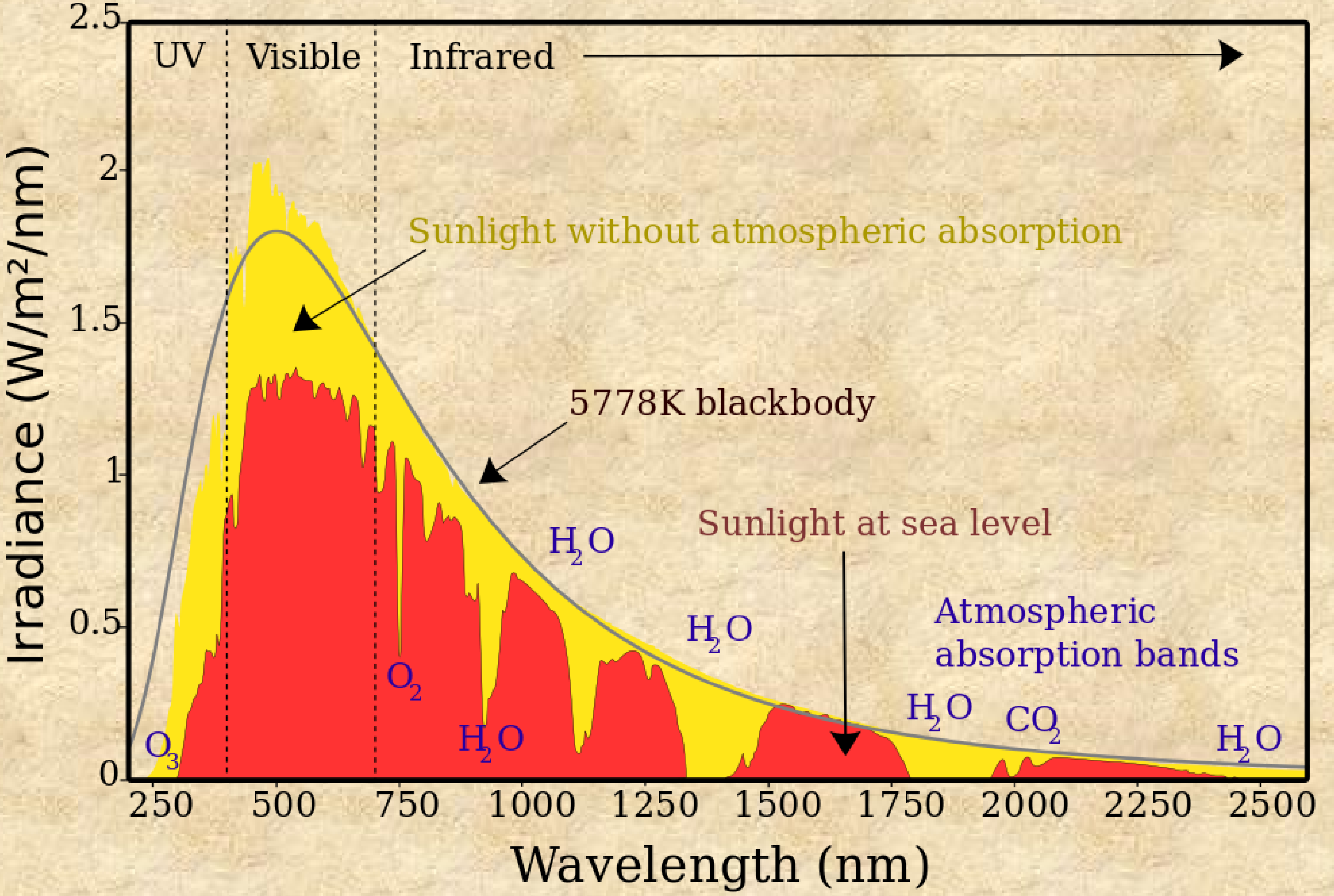
Solar Heating

- Passive solar heating – design structure to maximize absorption of solar energy
- Active solar heating – sunlight heats a fluid which is then circulated through the structure

Solar electricity

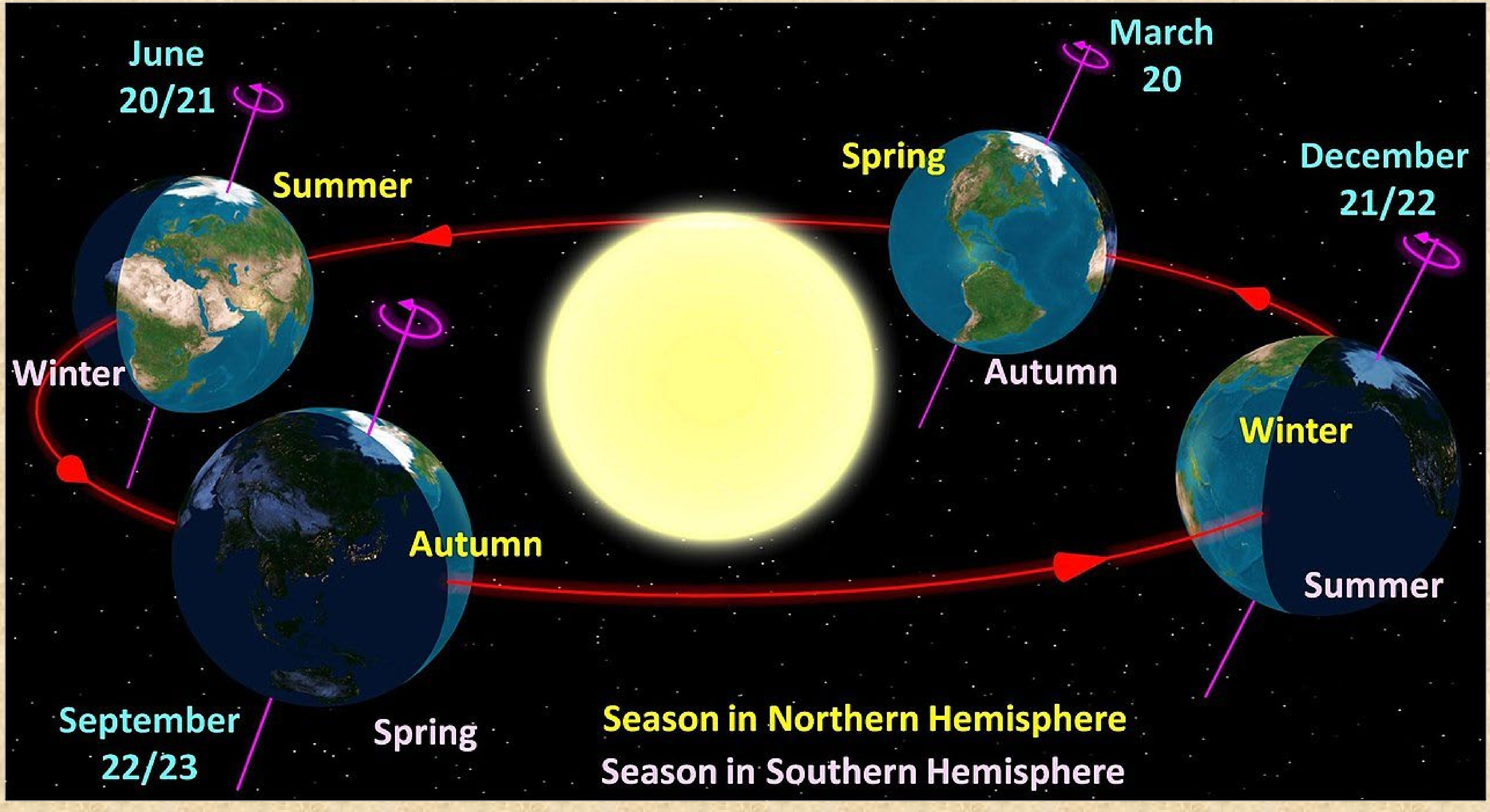
- Use solar energy to heat a fluid (water or some other working fluid) that can be flashed to steam to drive a turbine
- Direct conversion of sunlight to electricity (photovoltaics)

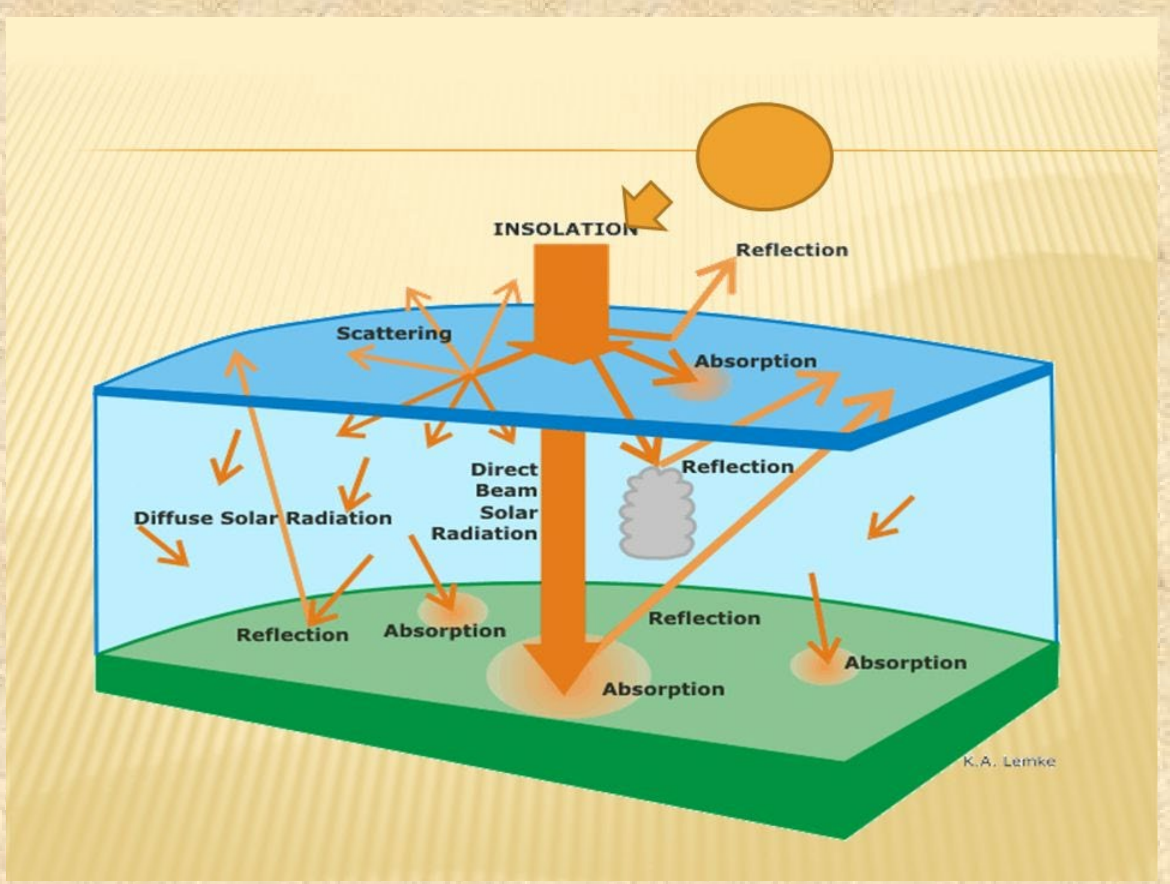
Spectrum of Solar Radiation (Earth)



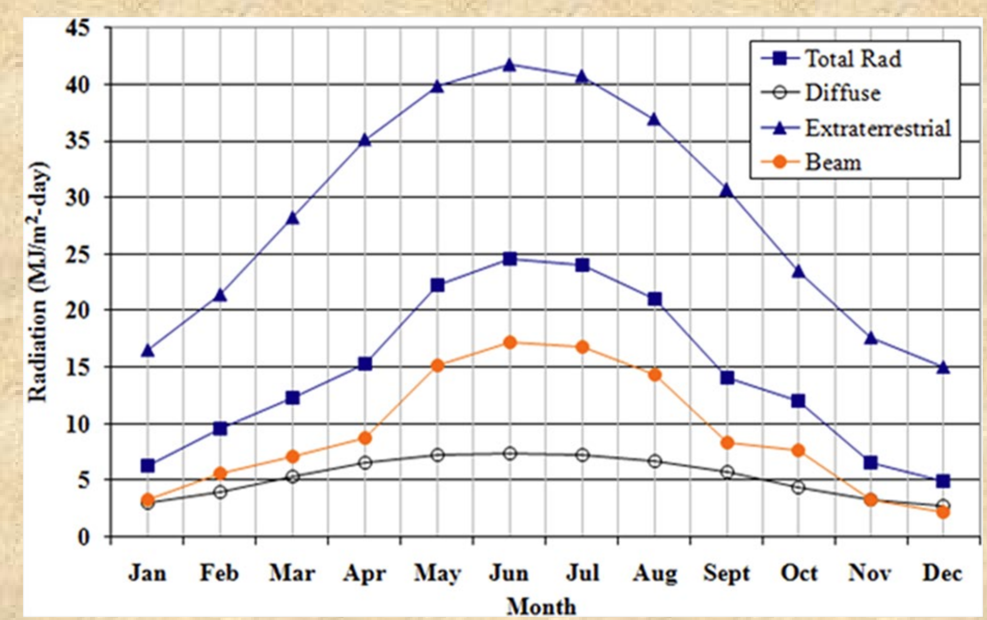
Solar constant – 1,365 W/m^2 (NASA estimate)

Winter solstice, Vernal equinox, Summer solstice, Autumnal equinox Northern Hemisphere

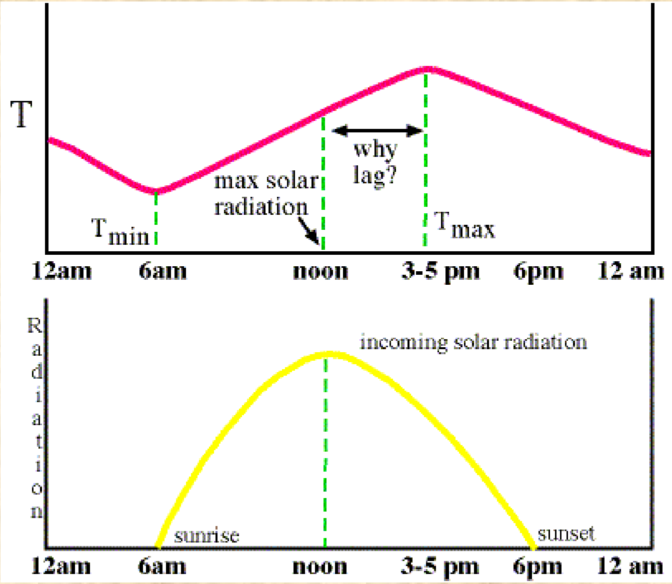




Insolation – incoming solar radiation which reaches the Earth's surface. There is both a seasonal and daily variation



Seasonal variations of diffuse irradiance versus beam irradiance for Northern Hemisphere



Daily variation in insolation

Available solar radiation

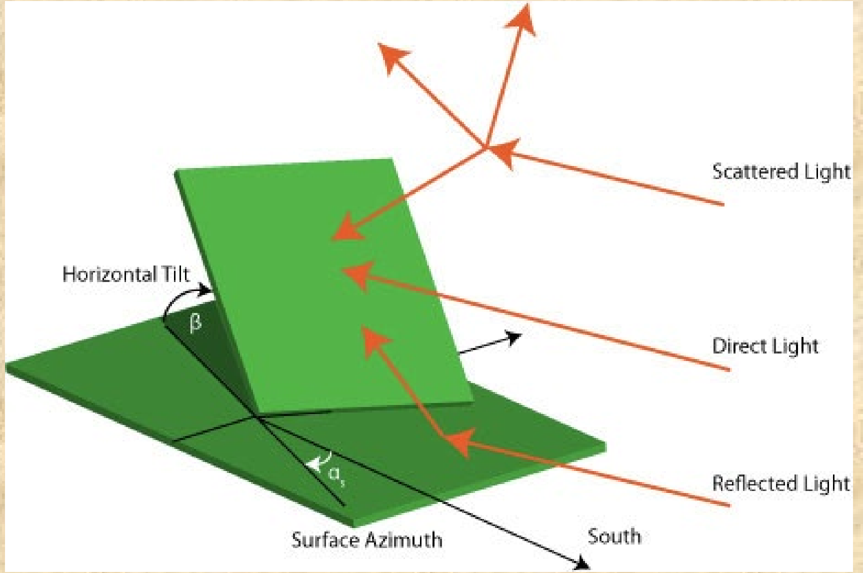
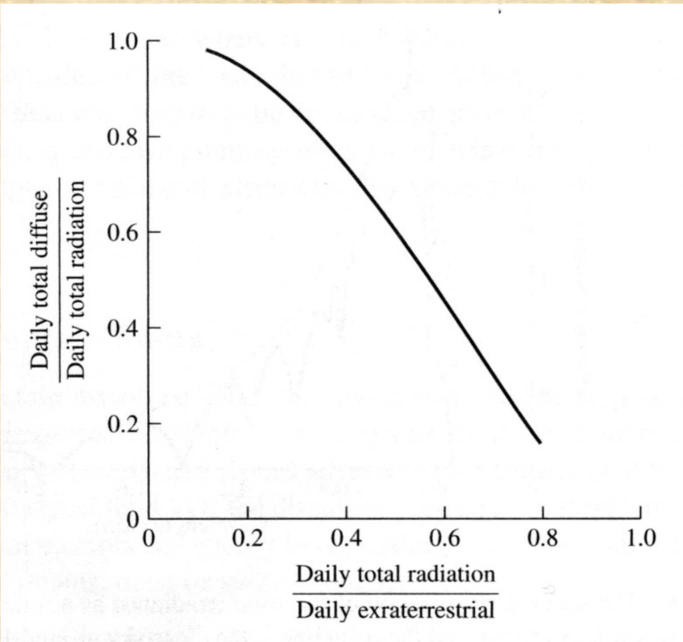


TABLE 8.4 Clear-Sky Irradiance at 40° N Latitude

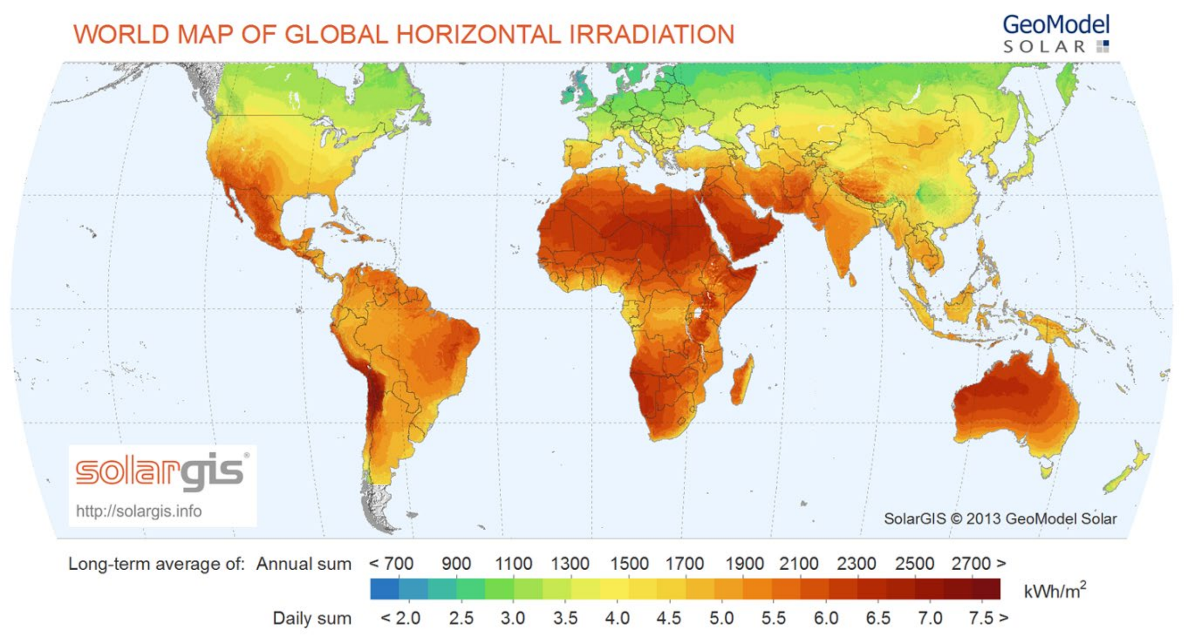
Position	Horizontal	40° tilt	Vertical	Direct normal
Daily total (MJ/m^2)				
21 Mar.	21.02	26.44	16.84	33.09
21 June	30.05	25.24	6.92	36.08
21 Sept.	20.29	25.28	16.08	30.73
21 Dec.	8.87	18.54	18.68	22.44
Annual average	20.06	23.88	14.63	30.58
Maximum hourly (MJ/m^2)				
21 Mar.	810	1027	656	968
21 June	958	911	309	879
21 Sept.	785	987	630	914
21 Dec.	451	867	829	898
Annual average	751	948	606	915

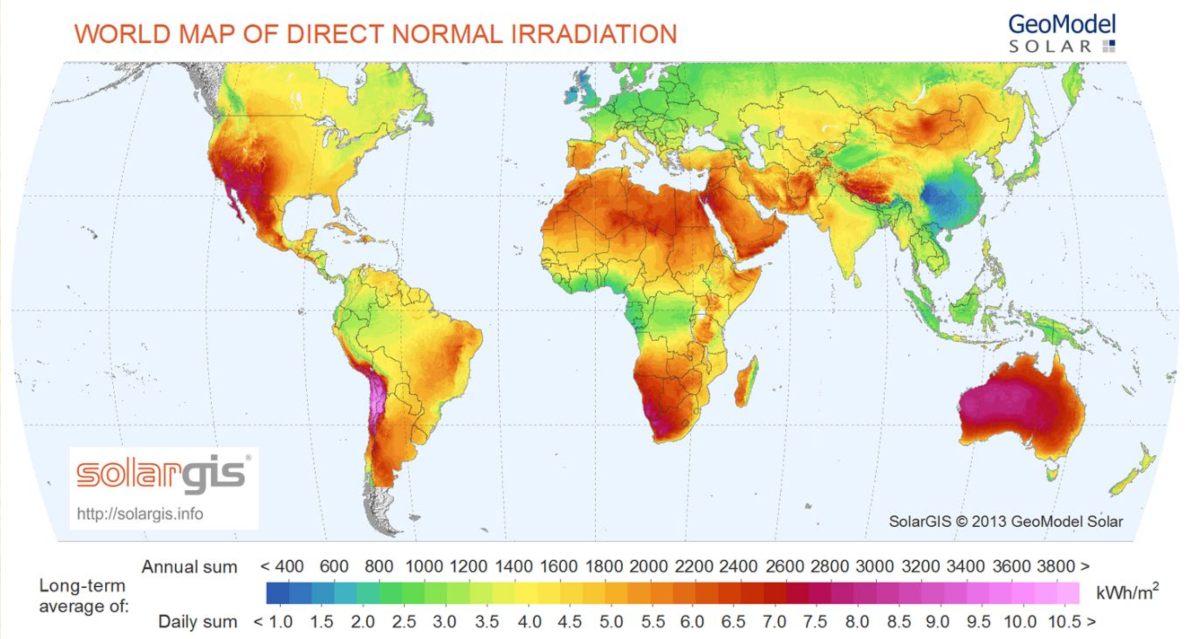
X-axis = *clearness index* = amount of total radiation received at surface relative to incoming solar radiation.

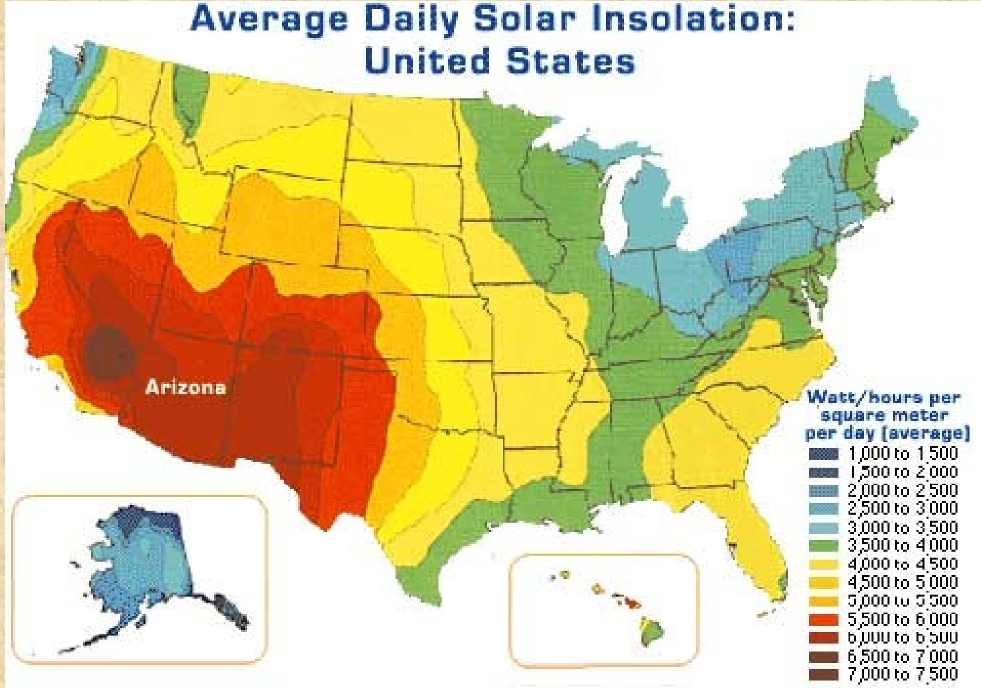
Y-axis = diffuse radiation relative to daily total radiation which is a measure of cloudiness



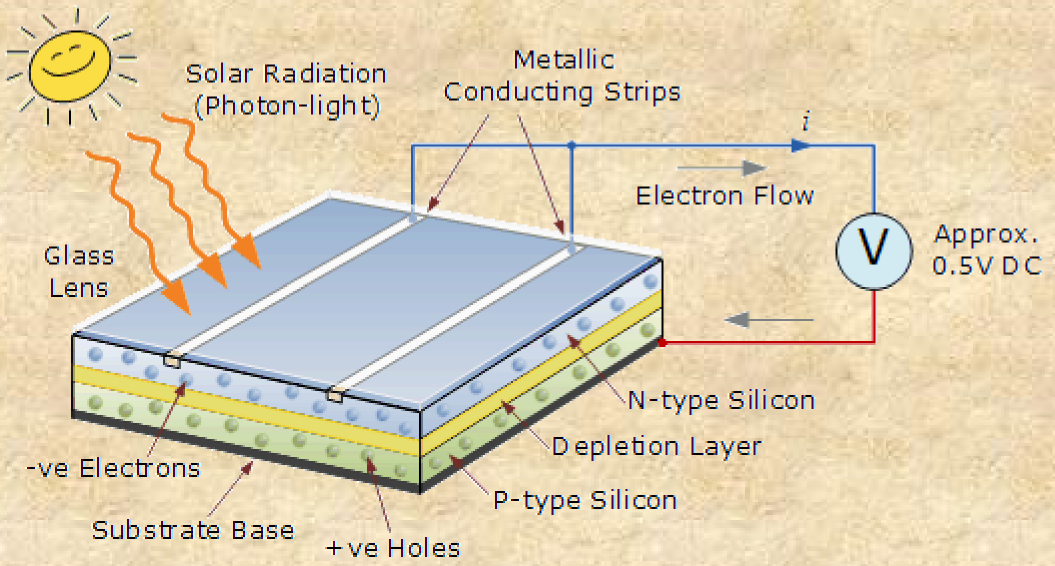
Available solar radiation as a function of latitude and type of radiation.

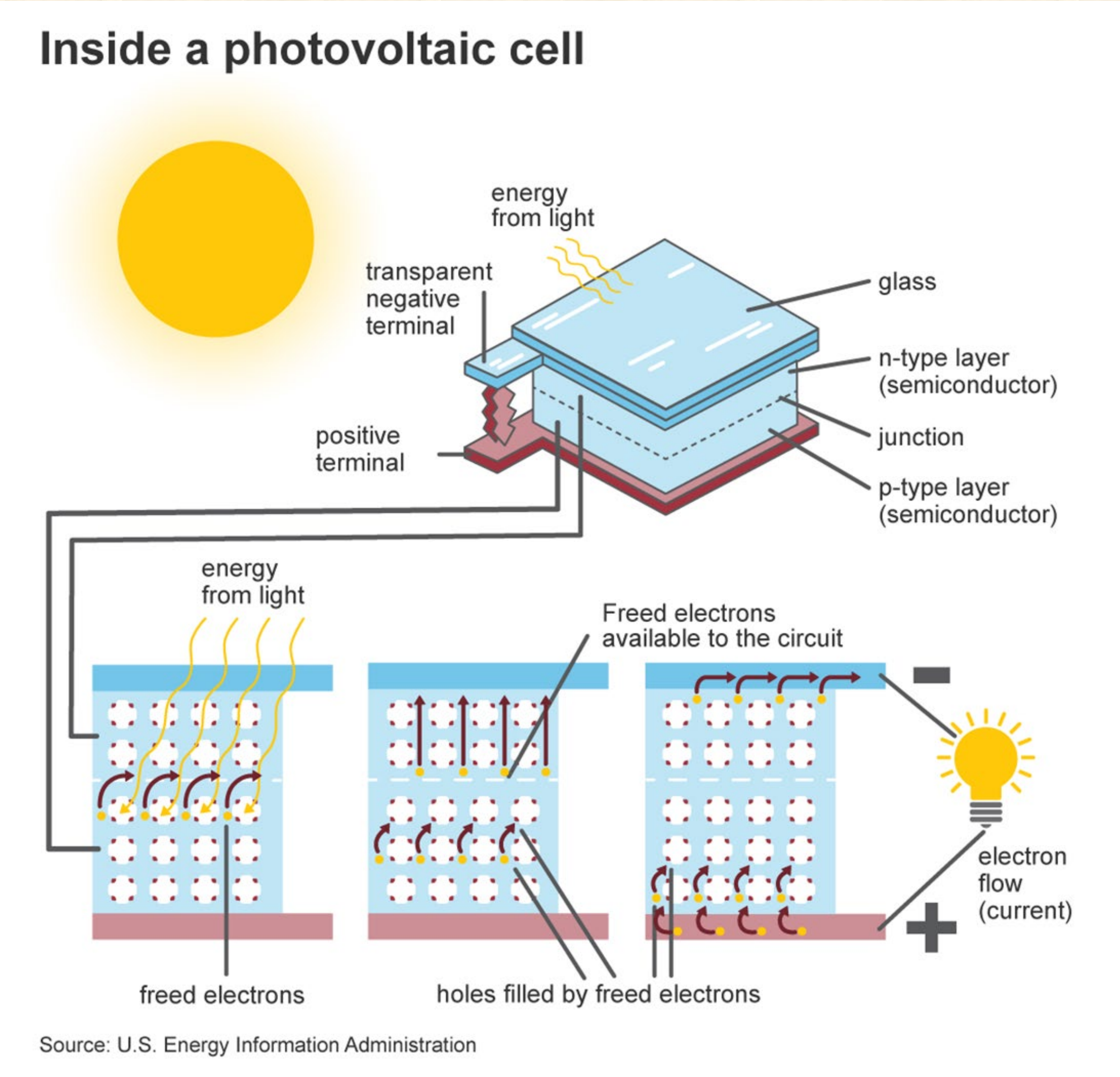






Photovoltaic cells



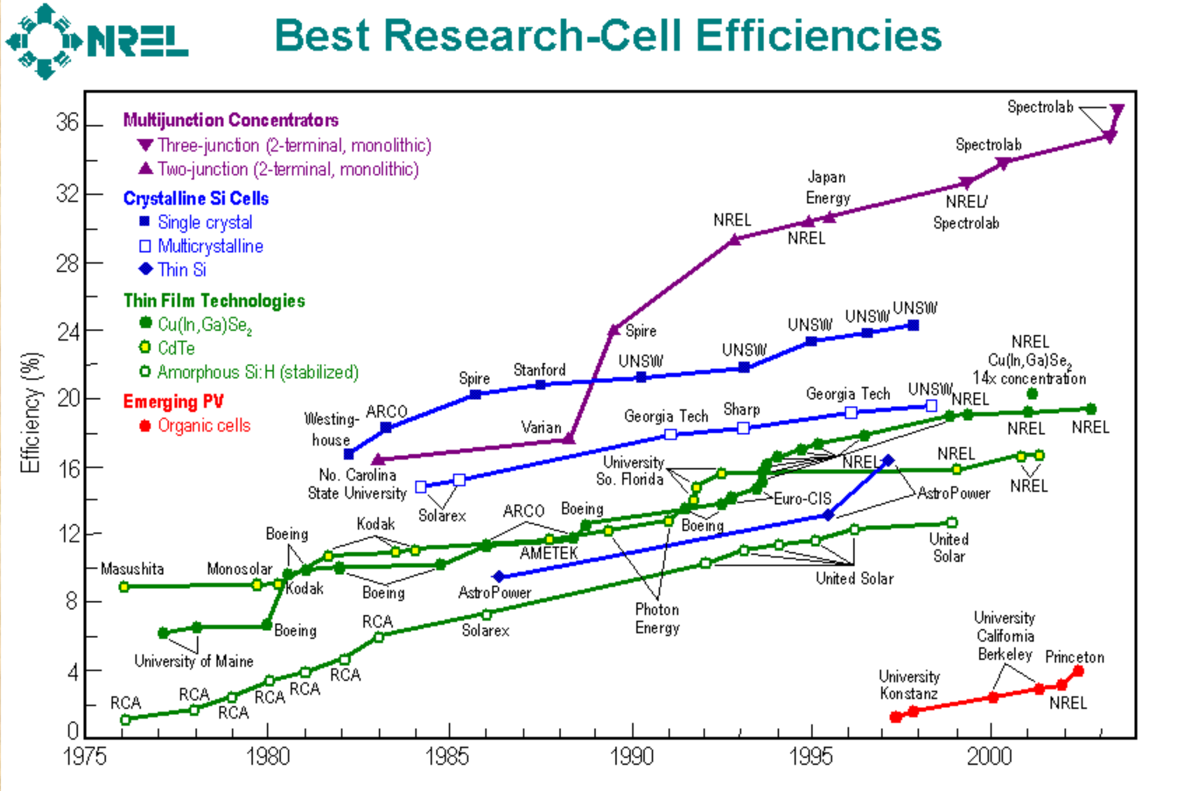


N-type layer – Si doped with P or As. Electron donors.

P-type layer – Si doped with B or Ga. Electron acceptors.

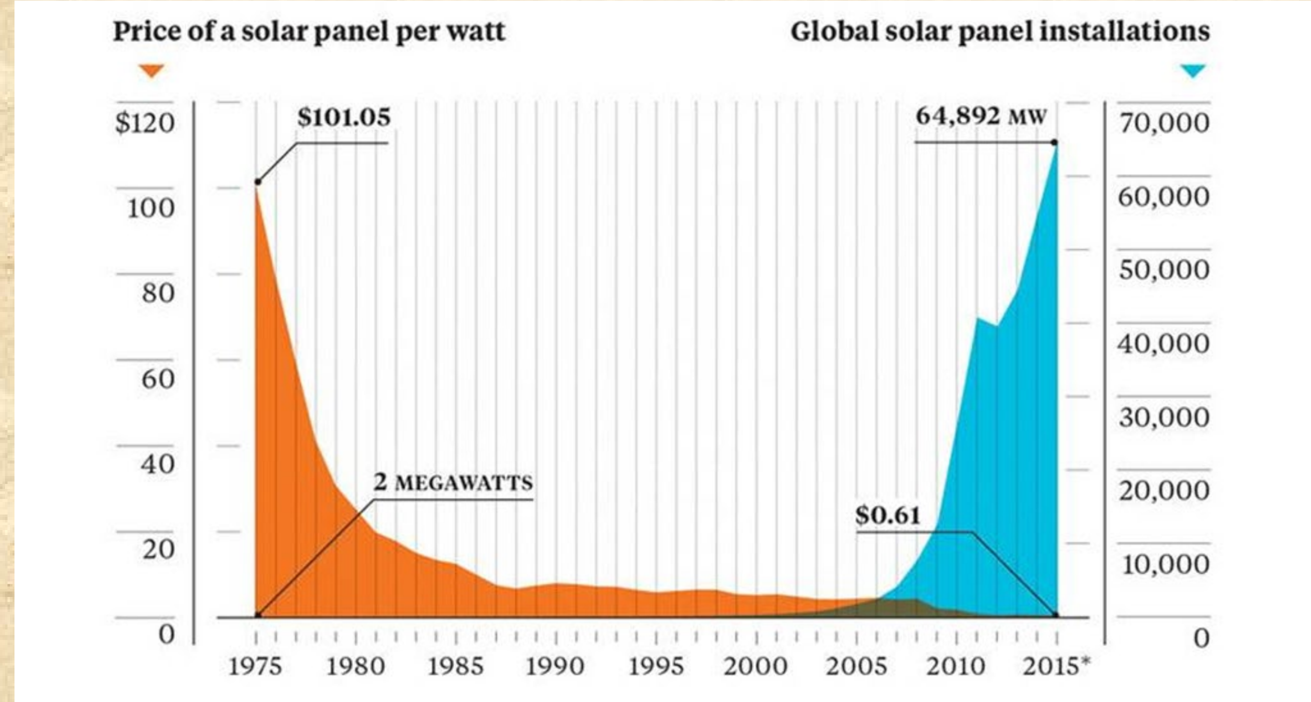
Solar cell efficiencies

PV Technology		Cell Conversion Efficiency	Module Conversion Efficiency
Crystalline	Monocrystalline Silicon (Si)	25.0%	14% - 16%
	Multicrystalline Si	21.3%	14% - 16%
	Gallium Arsenide (GaAs)	27.5 - 29.1%	N/A
Thin Film	Amorphous Si (a-Si)	13.6%	6% - 9%
	Cadmium Telluride (CdTe)	22.1%	9% - 12%
	CIS / CIGS	22.3%	8% - 14%



In some applications – individual homes, portable electronics, etc. the produced electricity is not distributed to the electric grid.

However, in many cases electricity generated locally is distributed to the grid. Since solar cells generate DC current, the current must be converted to AC using an inverter. The electricity from these sources must be balanced against base-load requirements.



Continued improvement in the design and manufacture of solar cells has led to decreasing cost. The result has been a significant increase during the early years of the 21st century in installed solar electricity capacity. Most of this increase has been associated with large scale photovoltaic systems.

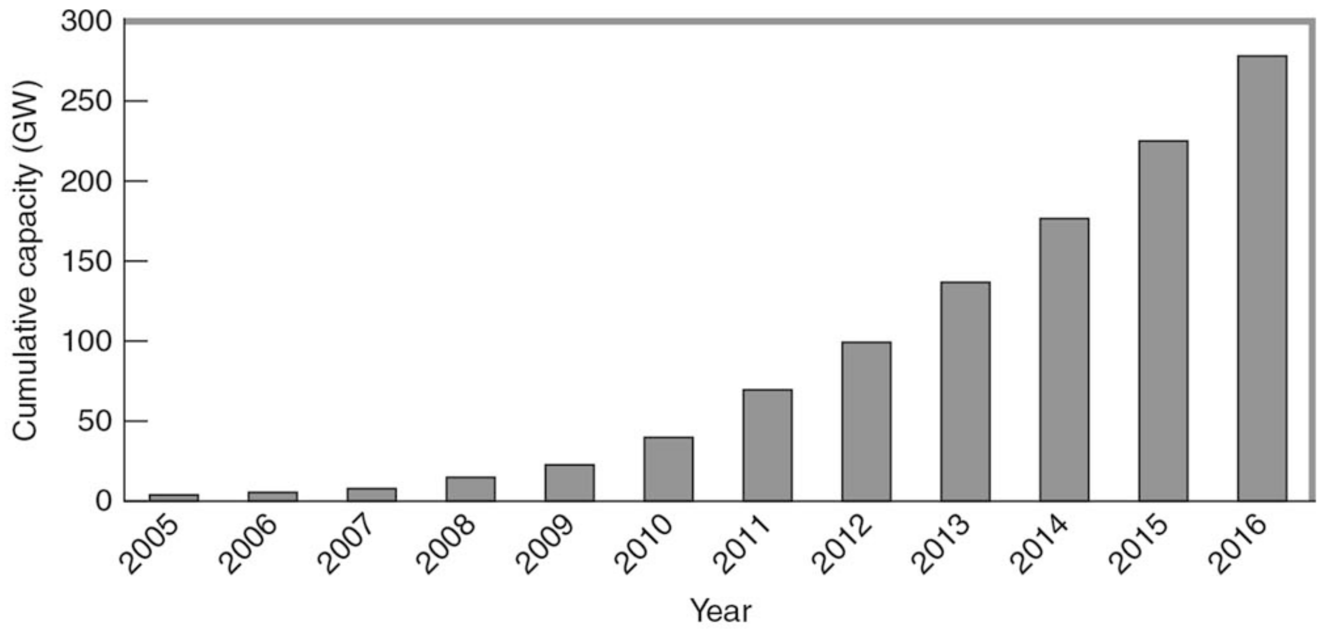
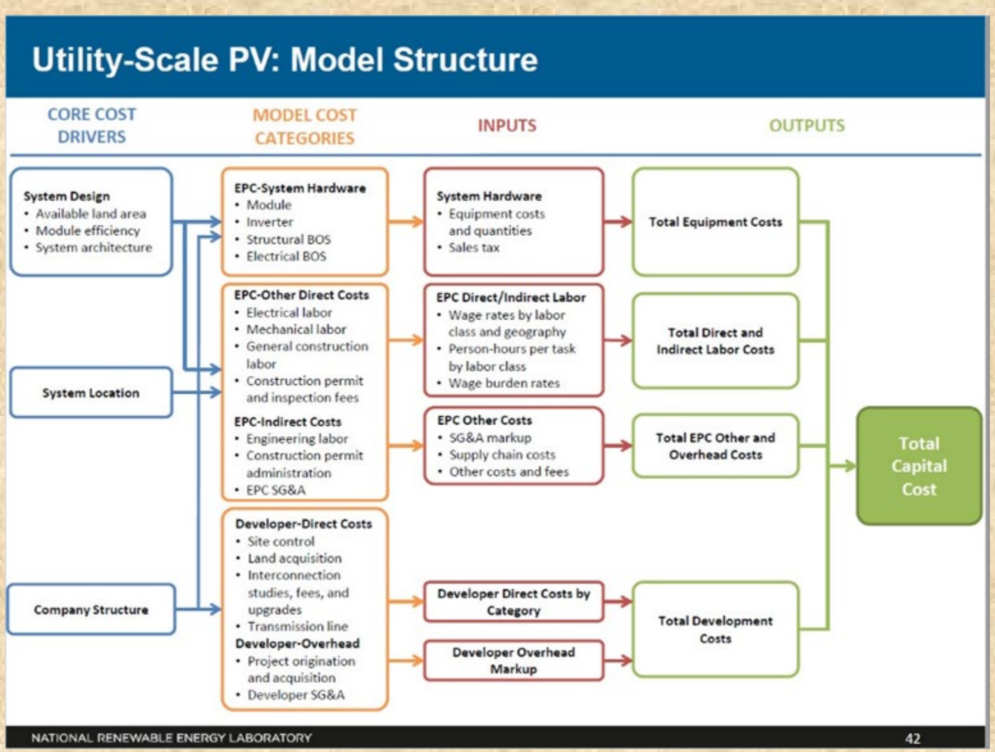
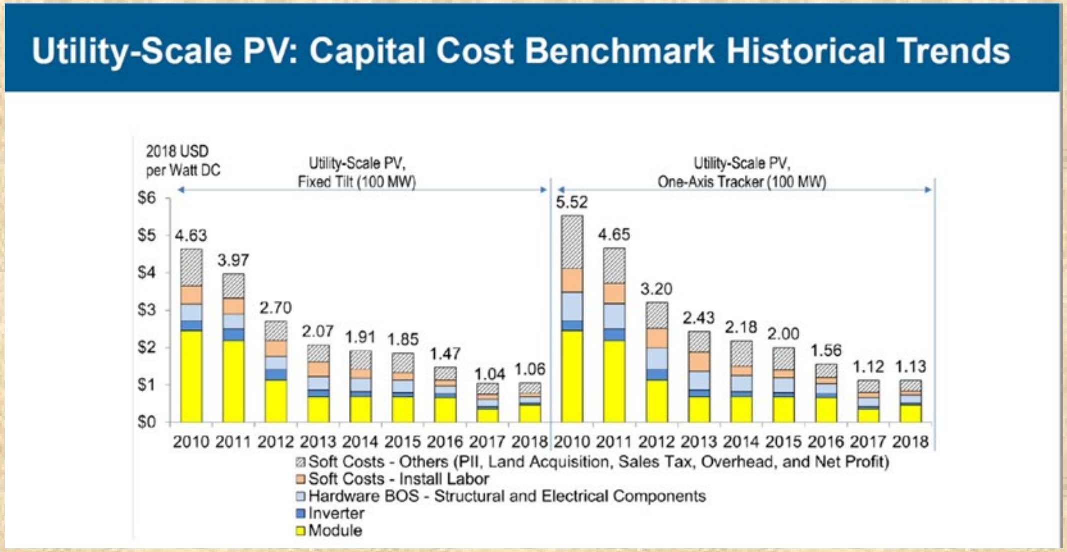


FIGURE 9.15

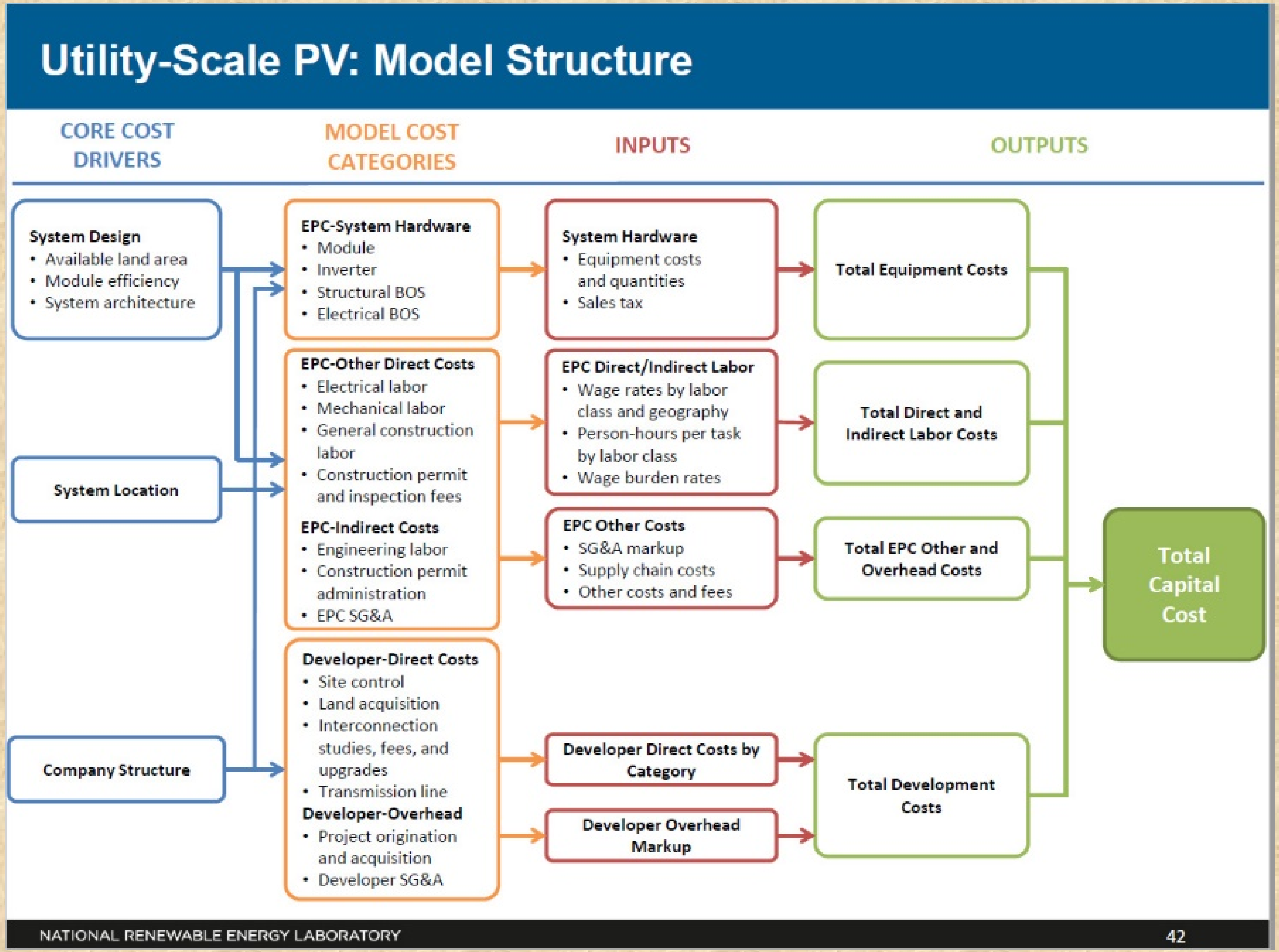
Global PV capacity grew at some 40% annually during the past decade. Essentially all of this PV growth is in grid-connected facilities.


Utility-Scale PV: Model Structure
CORE COST DRIVERS
MODEL COST CATEGORIES
INPUTS
OUTPUTS
System Design
• Available land area
• Module efficiency
• System architecture
System Location
Company Structure
EPC-System Hardware
• Module
• Inverter
• Structural BOS
• Electrical BOS
EPC-Other Direct Costs
• Electrical labor
• Mechanical labor
• General construction labor
• Construction permit and inspection fees
EPC-Indirect Costs
• Engineering labor
• Construction permit administration
• EPC SG&A
Developer-Direct Costs
• Site control
• Land acquisition
• Interconnection studies, fees, and upgrades
• Transmission line
Developer-Overhead
• Project origination and acquisition
• Developer SG&A
System Hardware
• Equipment costs and quantities
• Sales tax
EPC Direct/Indirect Labor
• Wage rates by labor class and geography
• Person-hours per task by labor class
• Wage burden rates
EPC Other Costs
• SG&A markup
• Supply chain costs
• Other costs and fees
Developer Direct Costs by Category
Developer Overhead Markup
Total Equipment Costs
Total Direct and Indirect Labor Costs
Total EPC Other and Overhead Costs
Total Development Costs
Total Capital Cost
NATIONAL RENEWABLE ENERGY LABORATORY
42


Utility-Scale PV: Capital Cost Benchmark Historical Trends
2018 USD per Watt DC
Utility-Scale PV, Fixed Tilt (100 MW)
Utility-Scale PV, One-Axis Tracker (100 MW)
$6
$5
$4
$3
$2
$1
$0
4.63
3.97
2.70
2.07
1.91
1.85
1.47
1.04
1.06
5.52
4.65
3.20
2.43
2.18
2.00
1.56
1.12
1.13
2010 2011 2012 2013 2014 2015 2016 2017 2018 2010 2011 2012 2013 2014 2015 2016 2017 2018
Soft Costs - Others (PII, Land Acquisition, Sales Tax, Overhead, and Net Profit)
Soft Costs - Install Labor
Hardware BOS - Structural and Electrical Components
Inverter
Module


550 Mw Desert Sunlight solar power installation


25.7 MW Lauingen Energy Park in Bavarian Swabia, Germany



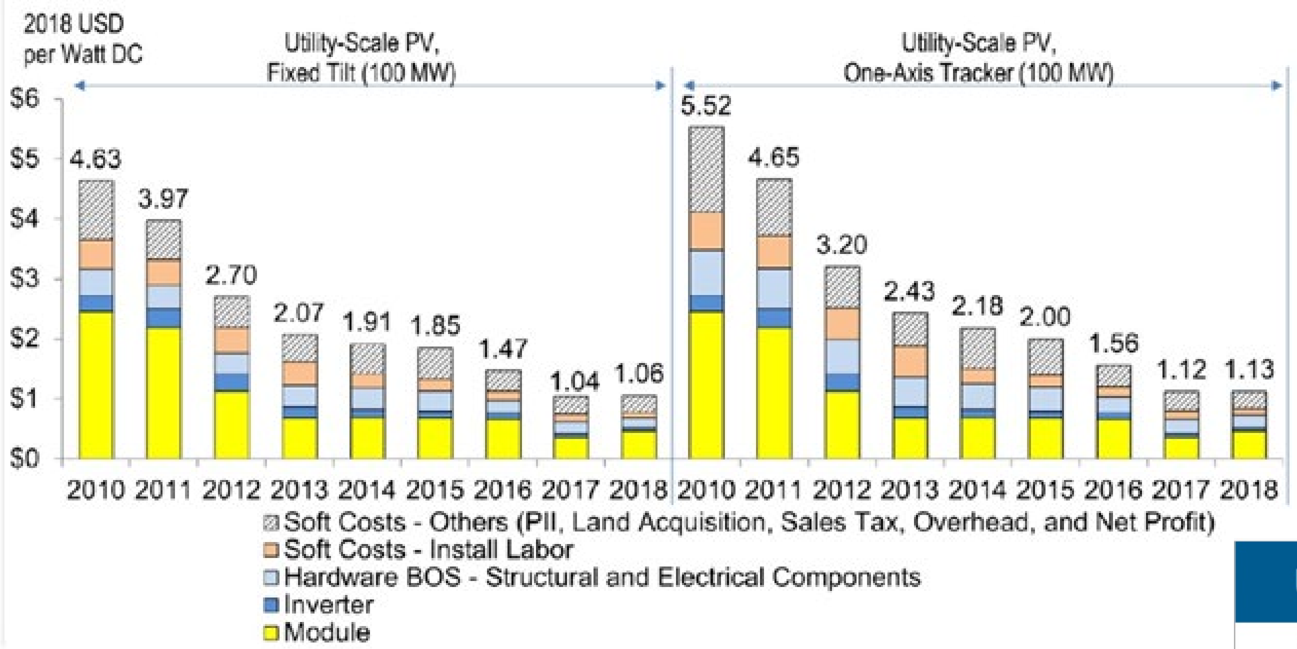
EPC = Engineering, Procurement, and Construction

BOS = Balance of System

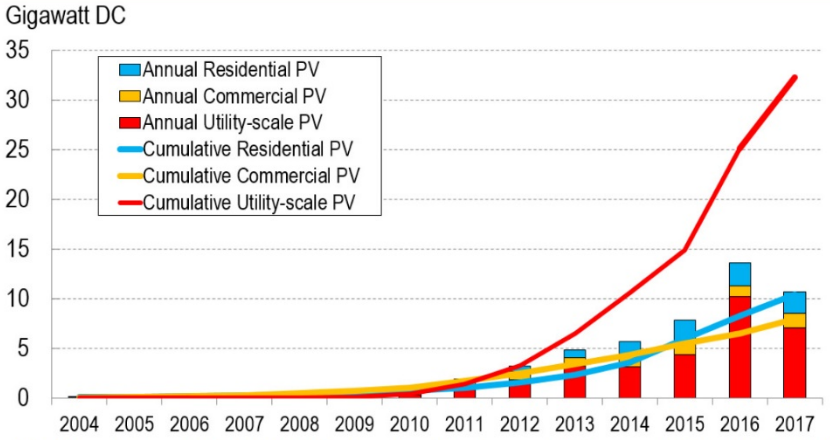
SG&A = Selling, General and Administrative Expenses

[US Solar Photovoltaic System Cost Benchmark - NREL]

Utility-Scale PV: Capital Cost Benchmark Historical Trends



US Solar PV Market Growth

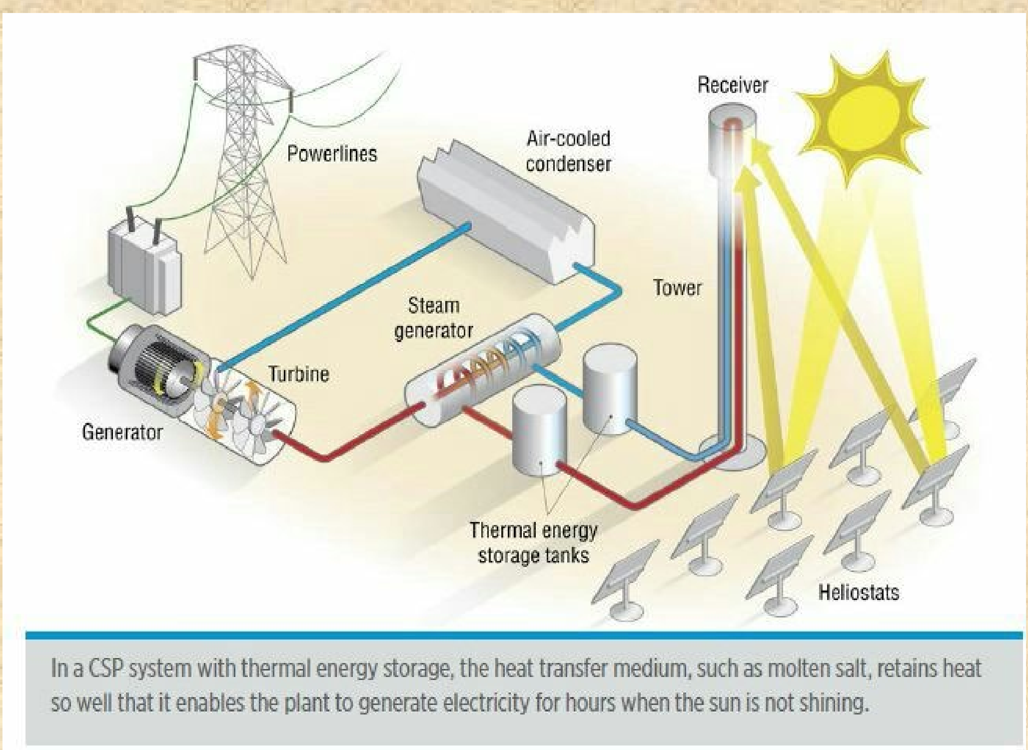


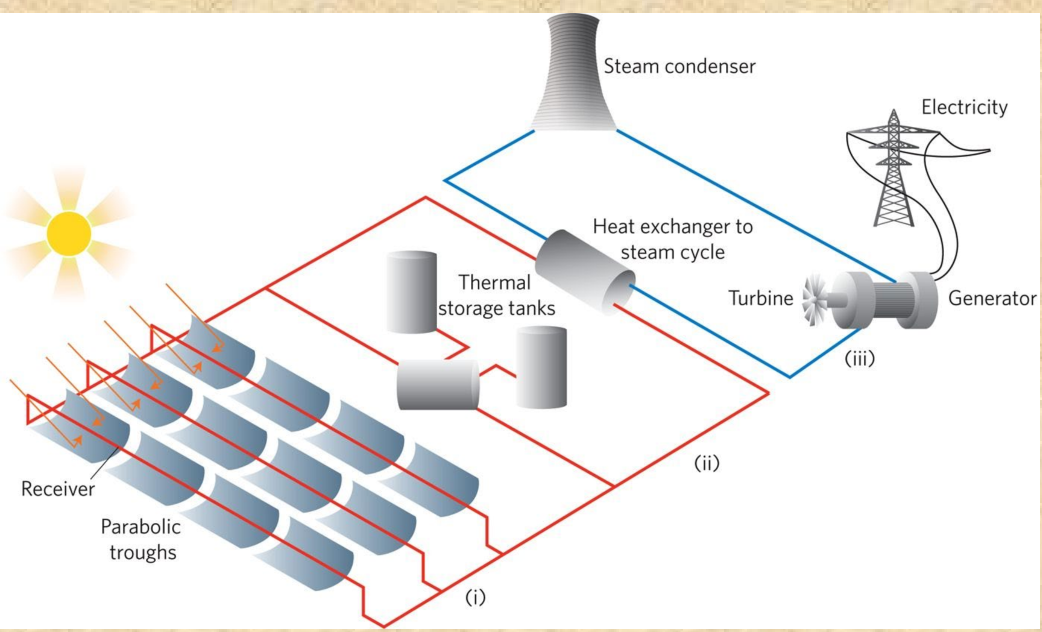
U.S. PV market growth, 2004–2017, in gigawatts of direct-current (DC) capacity (Bloomberg 2018)

Thermal Solar Power

Ivanpah solar power plant – flat solar mirrors focus sunlight on an absorber. 392 MW gross

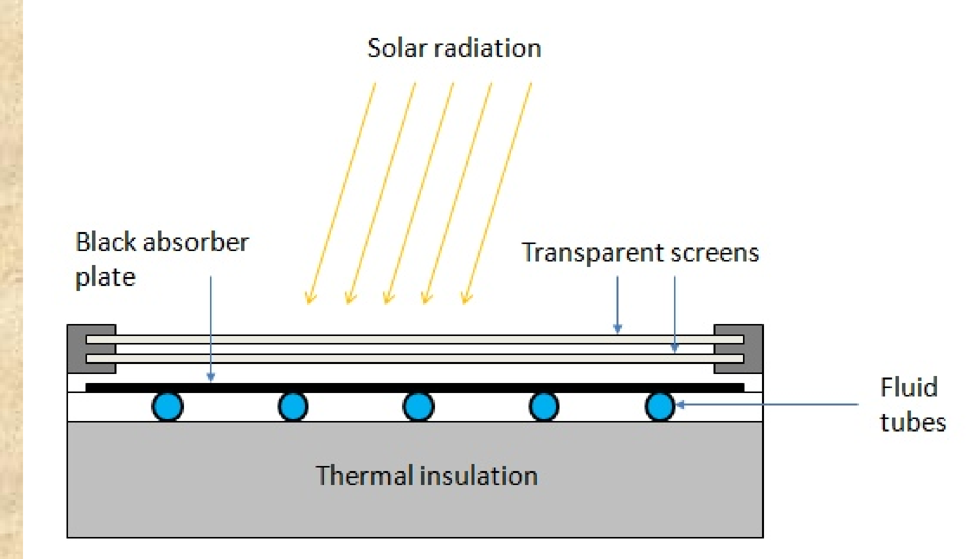
Gemasolar tower power plant – molten salt serves as the heat-transfer fluid and energy-storage medium. 19.9 MW





Concentrated solar power (CSP) systems

Flat plate collectors



Schematic of a flat plate solar collector. The solar radiation is absorbed by the black plate and transfers heat to the fluid in the tubes. The thermal insulation prevents heat loss during fluid transfer; the screens reduce the heat loss due to convection and radiation to the atmosphere.

$q = \beta I - U(T_c - T_a)$

q = net unit heat flux collected in storage system

β = fraction of incoming radiation absorbed by collector plate

I = incoming solar radiance

U = overall heat transfer coefficient

T_c = temperature collector

T_a = temperature environment

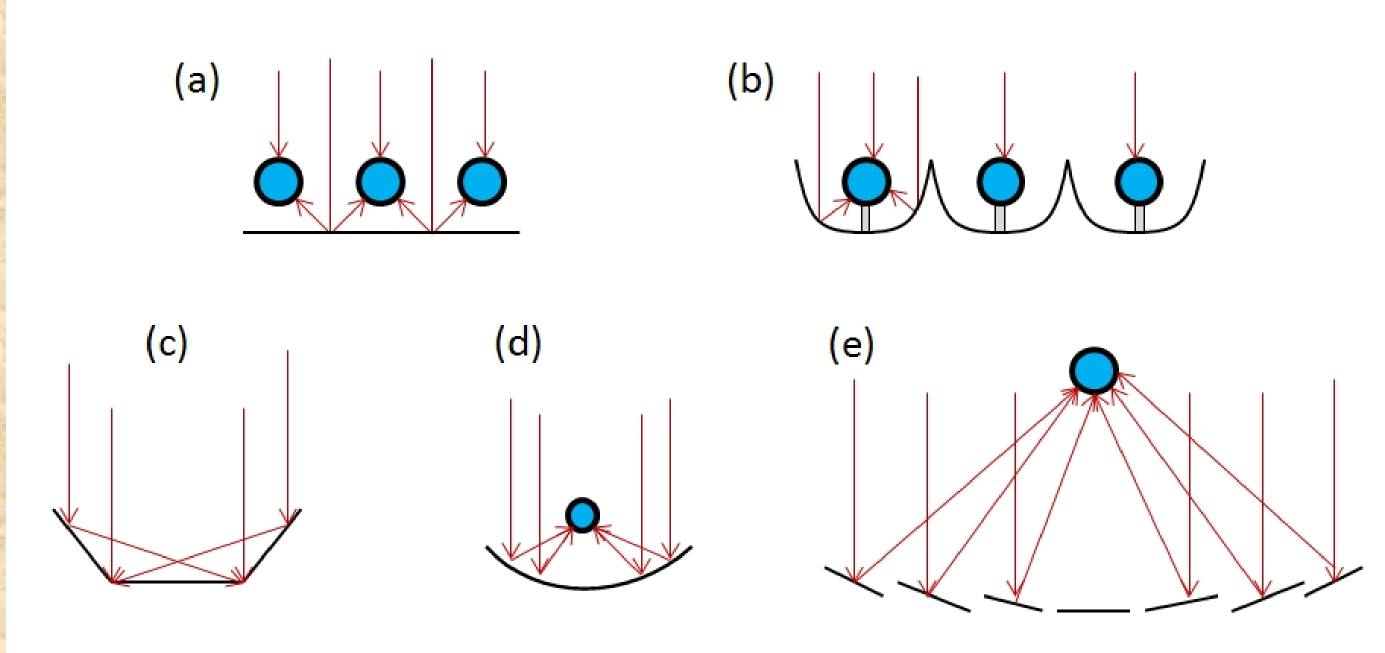
$(T_c)_{max} = T_a + \beta I/U$

$\eta = q/I = \beta - [U(T_c - T_a)]/I$

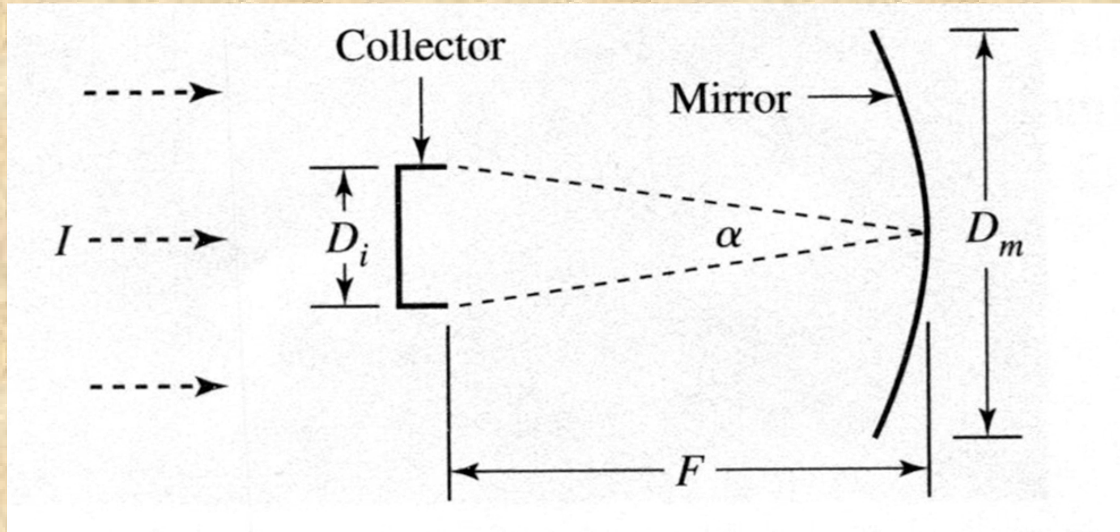
η = collector efficiency

Typical values for β (0.8) and U (5 W/m^2K)

Focusing Collectors



Types of concentrating sunlight collectors: (a) tubular absorbers with diffuse back reflector, (b) tubular absorbers with specular cusp reflectors, (c) plane receiver with plain reflectors, (d) parabolic concentrator, (e) array reflectors (heliostats) with central receiver. Concentration of light on the receiver is achieved by shaping the reflectors (mirrors) around the receiver.



Spherical mirror:
$CR = 1.154E4(D_m/F)^2$

Cylindrical mirror:
$Cr = 1.0752E2(D_m/F)$

CR = concentration ratio

$(T_c)_{max} = T_a + [\beta I(CR)]/U$

$\eta = q/I = \beta - [U(T_c - T_a)]/[I(CR)]$

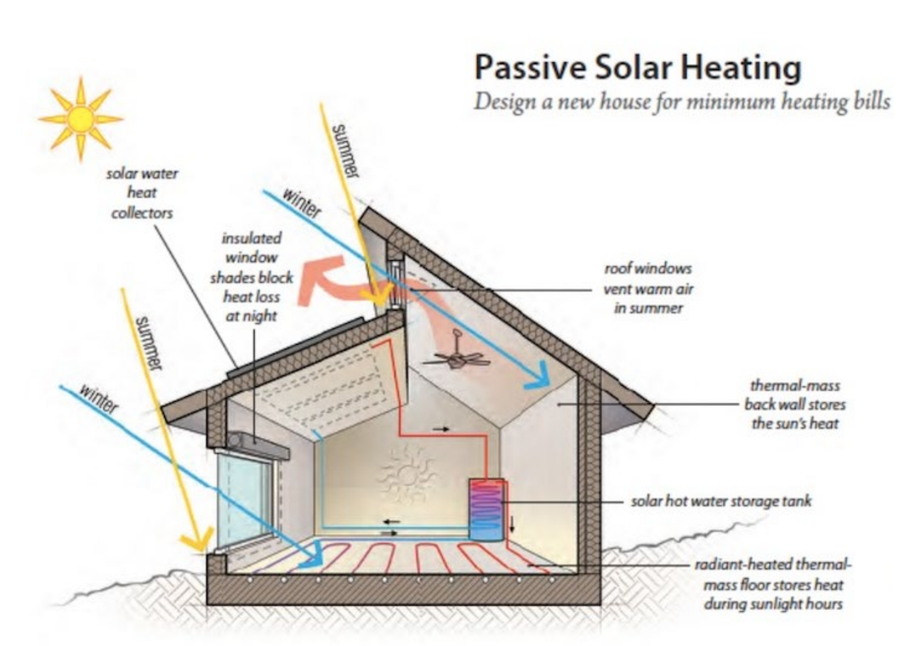
$D_m/D_i = D_m/\alpha F = 107.5(D_m/F)$

D_m = mirror dimension

D_i = image dimension

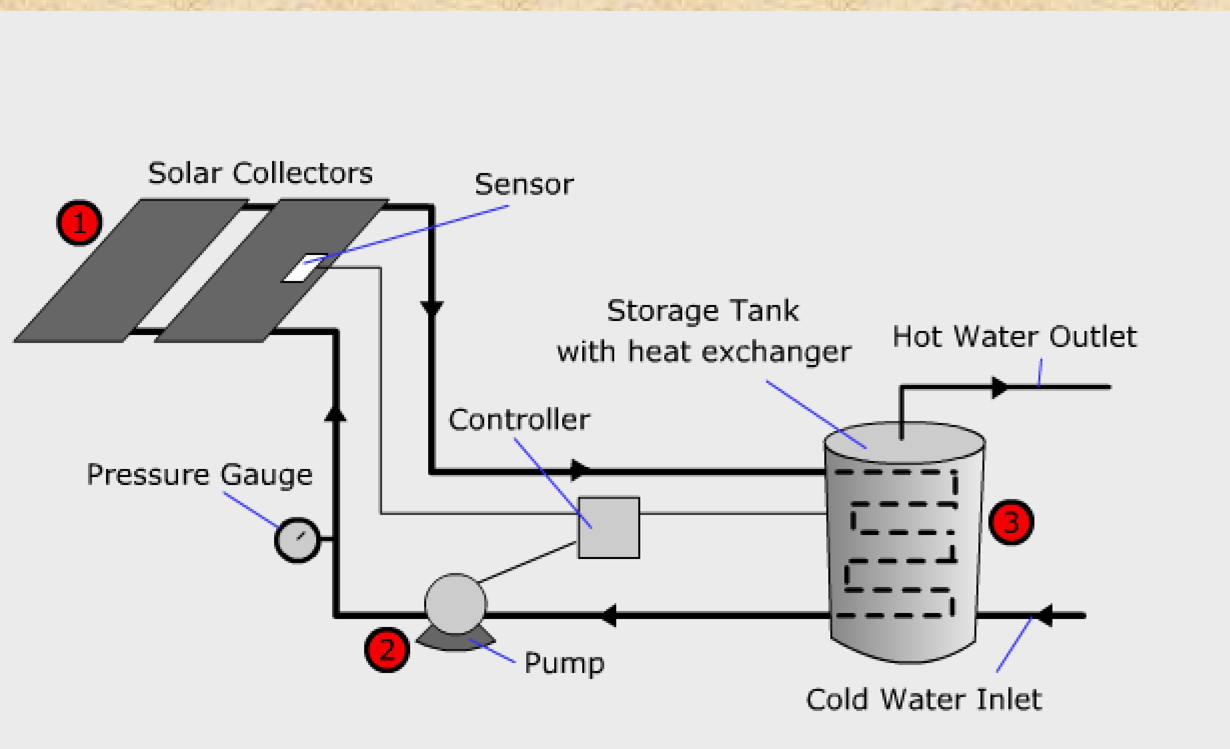
α = 9.3E-3 radian = angle that the sun subtends when viewed from the Earth

F = focal length



Northern Hemisphere Design

- South facing windows oriented within 30^{o} of south
- Thermal mass – commonly brick, concrete, stone, and tile
  - Direct gain – sunlight directly strikes thermal mass that makes up interior of building
  - Indirect gain – Trombe Wall – thermal mass between south facing windows and interior of home. Slowly releases heat throughout the day
  - Isolated gain – sun room (solarium)
- Distribution mechanisms – convection, radiation, conduction. May be augmented by small fans
- Control strategies – roof overhangs, vents, blinds, awnings, etc.



Active solar heating

- Flat plate collectors are most common
- Working fluid (water, non-toxic propylene glycol) absorbs and transfers heat
- Controller operates a circulating pump to move the fluid through the collector
- Fluid goes to storage tank with heat exchanger
- Hot water is distributed to the house via radiant floor, hot water baseboards or radiators, or a central forced-air system